ADVANCED STATIC ENERGY CONVERSION FOR SPACE NUCLEAR POWER SYSTEMS

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ABSTRACT

Several advanced static thermal-to-electric conversion technologies have been investigated as potential alternatives to conventional thermoelectrics and thermionic converters. The goal has been to identify static converters with efficiencies that are competitive with dynamic systems. Thermophotovoltaic, AMTEC, HYTEC, thermo-acoustic and liquid metal MHD are the principal technologies studied. Of these, AMTEC has received the most attention and is now the most mature. Several key fundamental issues have been resolved and engineering issues are now being addressed. Thermophotovoltaics has the advantage of extensive photovoltaic systems heritage, however the requirements to maintain a highly efficient optical cavity for long periods and to provide an efficient means of cooling the cells to near room temperature are challenges that must be addressed. Experiments have begun to characterize the HYTEC converter and basic technical issues are now being identified for further study. Thermoacoustics has received less attention and system concept designs are not yet developed. Liquid metal MHD experiments have not yet demonstrated performance consistent with theoretical projections and substantial obstacles to high efficiency performance remain.

INTRODUCTION

Static thermal-to-electric energy converters have historically been the mainstay for space nuclear-electric power systems. Radioisotope power systems have extensively utilized thermoelectric converters based upon the Seebeck effect to provide reliable, long lived power sources for a wide range of space exploration missions. Static devices have also been the converters of choice for space reactor-based systems, including those under development today that would employ either thermionic or thermoelectric converters. Both thermoelectric and thermionic conversion systems offer the durability of a static system without moving mechanical parts and the reliability afforded by the redundant connection of many devices in series-parallel networks having no single point failure mechanisms.

However, both thermoelectric and thermionic systems operate at thermal-to-electric conversion efficiencies that are typically below 10%. This can result in significant mass penalties in both nuclear heat source and heat rejection systems when compared to system concepts that would utilize dynamic conversion systems. The cost and scarcity of radioisotope fuel exacerbates the impact of low conversion efficiency in radioisotope-based systems. In the case of thermionics, very high temperatures are typically required, giving rise to stringent materials requirements.

While high efficiency dynamic conversion systems are viable options for a variety of space nuclear power systems, work has also been carried out on other conversion concepts. The goal has been to achieve both the reliability attributes of a static converter and the high efficiencies of dynamic conversion systems, at heat source temperatures in the 1000K to 1300K range.

This paper will review the status of the most prominent static conversion concepts that have been studied in the laboratory and in system designs during the past ten years. Only closed loop concepts and those requiring no moving mechanical components throughout the entire cycle are considered. Three of those discussed (AMTEC, HYTEC and Thermophotovoltaics) provide the possibility of a high level of redundancy via the connection of many cells in series-parallel networks. Otherwise, efforts to improve the performance of thermoelectric (especially silicon-germanium) and thermionic converters have also been carried out. These results are reported elsewhere in this volume by Vining and Fleurial (1993), and Dahlberg et al. (1993).

THERMOPHOTOVOLTAICS

Thermophotovoltaic(TPV) energy conversion is based on the response of a photovoltaic cell to infrared photons emitted from a high temperature source. System concepts have considered both concentrated solar energy and nuclear-based heat sources. A schematic of a TPV converter configuration is shown in Figure 1. Efficient thermal-to-electric energy conversion requires that the source heat flux energy spectrum be matched to the response of the photovoltaic cell and also requires that the system design effectively contains photons within the cavity between emitter and cell.

The status of thermophotovoltaic conversion was reviewed in the proceedings of the First Symposium on Space Nuclear Power Systems (Ewell and Mondt, 1985). Since then significant progress has been made in the development of new photovoltaic cells, some having the potential for use in thermophotovoltaic applications. The result of these developments has been to expand the temperature range of possible thermophotovoltaic application.

Previously, studies were limited to silicon solar cells having a high (indirect) band gap requiring heat source emitters of more than 2000K (Horne et al. 1980). More recently, lower (direct and indirect) bandgap photovoltaic cells such as GaSb, GaInAs, InAs, AlInAs, InAsP and Ge have been considered for static thermal-to-electric conversion in the temperature regime around 1000K (Wolf 1986). The degree to which these materials have been characterized and the number of cells fabricated varies widely. Only GaSb has been both characterized and cell fabrication processes well developed.

The band gap of GaSb, developed for use in a GaAs/GaSb tandem solar cell, is 0.73eV. It is in the optimal band gap range calculated by Woolf (1986) for cells operating between 300K and 400K and using a 1473K radiant emitter. Present GaSb cell efficiencies are near 35% to wavelengths of 1.5 to 1.6 micron. Based upon these data, a GaSb-based radioisotope TPV converter concept design was proposed (Day et al. 1990 and Morgan et al. 1993). The concept is similar to the General Purpose Heat Source (GPHS) - Radioisotope Thermoelectric Generator (RTG), but would replace conventional SiGe converters with TPV cells. The design features the GPHS at a temperature of 1473K, radiating to cells at 350K giving a system efficiency of 12-14% at a specific power near 10W/kg. Most recent concept designs require active cooling of the cells using heat pipes.

These predictions are based on current cell technology, assuming that the cells can be backed and surrounded by a highly reflective (>95%) surface. Higher system efficiencies could be possible through the implementation of a narrow band pass filter between emitter and cell that would transmit infrared radiation tuned to the band gap of the TPV cell (see Fig. 1) and reflect all other wavelengths back to the emitter. Research on such filters for TPV application is still in the exploratory phase, however system efficiencies near 20% could be enabled by the development of such materials.

While the GaSb cell technology is relatively well characterized, no self-contained modules have been built or tested to verify system performance models. Such a demonstration is necessary in order to completely ascertain the feasibility of the GPHS-TPV concept. Questions involve the ability to maintain an efficient optical cavity over the lifetime of the mission, and a system design which would efficiently cool the converter elements to 350K. Radiation data on GaSb cells predicts an 8-10% power loss in 10 years using the GPHS. Otherwise, if the model projections are accurate, significant mass and fuel savings would be possible in comparison with the efficiency (7%) and specific power (6 W/kg) of the GPHS-RTG.

No recent studies of TPV conversion for space <u>reactor</u> power systems have been reported. Such a system could also utilize the results of research now underway on selective emitter materials that are tuned to the band gap of specific solar cells. Such materials, including rare earth oxides, are being investigated for terrestrial TPV applications and would have an impact similar to the filter approach discussed above. Again, the goal is to identify an emitter-converter combination that would enable system efficiencies near 20%, or more.

ALKALI METAL THERMOELECTRIC CONVERSION - AMTEC

The alkali metal thermoelectric converter, AMTEC, is a thermally regenerative electrochemical cell based on the sodium (or possibly potassium) ion conductive properties of beta"-alumina solid electrolyte (BASE) (Weber 1974). The operating cycle of the AMTEC is illustrated in Figure 2a. A closed vessel is divided into a high-temperature/pressure region in contact with a heat source and a low-temperature/pressure region in contact with a heat sink. These regions are separated by a barrier of BASE which has an ionic conductivity much larger than its electronic conductivity. The high-temperature/pressure region contains liquid sodium a T_2, and the low-pressure region contains mostly sodium vapor and a small amount of liquid sodium at T_1. Electrical leads make contact with a (positive) porous electrode which covers the low pressure surface of the BASE and with the high temperature liquid sodium (negative electrode). When the circuit is closed, sodium ions are conducted through the BASE due to the difference in vapor pressures (or chemical activity) across the BASE, while electrons flow to the porous electrode surface through the load producing electrical work. Sodium is recirculated by an electromagnetic pump or capillary pumped loop.

AMTEC systems have been considered in several space and terrestrial power system applications with nuclear, solar and combustion heat sources. System efficiencies have typically been projected to be near 20%. Bankston et al. (1984) reviewed the status of AMTEC technology at the First Symposium on Space Nuclear Power Systems, and many papers have appeared in these and other Symposia volumes. During this period, significant progress has been made on some key technical issues. Of particular importance has been progress in long life electrode development, and demonstration of high efficiency performance in laboratory cells.

Two families of electrodes have been identified as being capable of operating at high power density with very long lifetime potential (ten years or more). Rhodium-tungsten electrodes (Williams et al. 1990 and Ryan et al. 1993) and titanium-nitride electrodes (Hunt et al. 1990) have both demonstrated near $0.5 W/cm^2$ power density. These are in the range of areal power densities needed to achieve thermal-to-electric conversion efficiencies near 20% in most system concepts studied that operate at 1100-1300K. In addition, modeling of grain growth of these materials, utilizing experimental data for several thousand hours at high temperature, shows that these electrodes should function for ten years or more.

A wide range of single and multi-cell AMTEC devices have been operated. A 36-cell system has been operated at 550W (Hunt et al. 1990), however, most test results are with single cell devices having output powers of less than 25W. Numerous cells have now been operated at high temperature for 1000 hours or more, with almost 1900 hours being achieved under load at 1050K and 13% efficiency in a cell at JPL (Underwood et al. 1993). This is the highest efficiency ever achieved in a self-contained AMTEC cell; it produced 14W. While most cells have been operated with electromagnetic pumps, several small cells have been operated using wick return pumping for sodium recirculation (Hunt et al. 1993). These have usually been small cells (1-5W), however, the wick return demonstration has significant implications for space (zero gravity) operation. In fact, a wick return cell has been operated in an inverted position pumping against gravity.

Since AMTEC parasitic losses generally scale with area, it should be possible to build cells over a wide range of sizes without significantly affecting efficiency. As a result, AMTEC space nuclear power system concept studies have considered the range from 10's of watts in radioisotope systems to a megawatt class, reactor based system (Sievers et al. 1992). All utilize multiple (smaller) unit cells connected in series-parallel networks to achieve voltage and reliability requirements. Most recent studies have been concerned with radioisotope systems using the General Purpose Heat Source. Efficiencies near 20% and specific powers near 20W/kg are projected for most such concepts studied to date. These include both cells integrated with and radiatively coupled to the GPHS for small ($\leq$1 kW) systems, and remotely heated cells via an intermediate heat transfer loop for larger (multi-kilowatt) systems. Figure 2b shows a unit cell design for space applications.

In summary, AMTEC technology has progressed to the point where most fundamental issues have been resolved. However, other issues relating to system design and performance must now be addressed based on specific mission requirements. For example, optimum cell designs and multi-cell module designs must be developed, fabricated, and tested. In this way, system performance and lifetime projections can be verified or modified. Also, a space flight demonstration may be required to verify liquid sodium flow and management techniques and to evaluate the stability of the BASE under launch conditions.

HYDROGEN THERMAL-TO-ELECTRIC CONVERSION - HYTEC

The relatively recent hydrogen thermal-to-electric converter, HYTEC, is another in the family of thermally regenerative electrochemical systems that has the potential to produce power in practical devices (Roy 1987). In this case it utilizes a lithium or lithium-sodium liquid circulating loop to circulate the working fluid, hydrogen. Power is produced via a metal electrode/molten salt/metal electrode electrochemical cell. A schematic of the cycle is shown in Figure 3a. The electrochemical cell diagram is in Figure 3b. Key points in the cycle are the electrochemical cell and a decomposition retort. A voltage is produced in the electrical cell due to hydrogen activity difference across the electrode/electrolyte/electrode system. Power is produced when hydride ions are conducted through the molten salt electrolyte and then react to form a metal hydride mixture with the circulating liquid metal(s). Heat is input at the decomposition retort where hydrogen is separated from the hydride mixture to return to the electrochemical cell in the gas phase for subsequent reaction in the electrochemical cell. Recirculation of the working fluid is achieved by an electromagnetic pump.

The advantages offered by a HYTEC system are similar to those for AMTEC. They include the potential for high efficiency (near 20%), relatively lightweight converter mass, no moving mechanical parts, and modularity (since parasitic losses are dependent on electrode area). Again, multiple cell systems are preferred to meet voltage and reliability requirements. An advantage is the fact that the power producing step takes place at relatively moderate heat rejection temperatures (approximately 850-900K for some reactor applications).

Recently, progress has been made in selecting a promising HYTEC working fluid which has desirable properties in terms of the equilibrium hydrogen vapor pressure of the working fluid as a function of temperature (Roy et al. 1993). Also, progress has been made in evaluating metal membranes which have fairly favorable hydrogen permeability, as well as some degree of stability under cell operating conditions. To date, demonstration of anticipated high device power densities in the system configurations proposed has not been achieved (0.014 W/cm^2 has been achieved and accurately predicted, compared with 0.02 - 0.04 W/cm^2 employed in system analyses) in the laboratory and a quantitative theoretical model is not yet formulated. Thus, a better understanding of the potential losses occurring at the power producing step is needed, including information on hydride ion mobility in the electrolyte, the kinetics of charge transfer processes at the electrode/electrolyte interface, and hydrogen permeability through the selected electrodes under HYTEC conditions. Experiments that provide this information will allow the ultimate potential of HYTEC to be assessed.

System studies typically place HYTEC in a reactor-based power system (Salamah et al. 1992). Coupled with an SP-100 type reactor system efficiencies between 17% and 23% have been predicted with a specific mass as a low as 12.5kg/kw. If the, as yet unknown, losses observed in the laboratory in the power producing step can be identified and reduced, then HYTEC could become a viable, high efficiency static converter option for future space nuclear power systems.

THERMOACOUSTIC POWER CONVERSION

Thermoacoustic energy converters convert thermal energy to acoustic energy; a transducer then converts the acoustic energy to electricity (Wheatley et al. 1983 and Swift 1988). A schematic of an acoustic engine is shown in Figure 4 and "a dozen or so working engines have been built in several laboratories" (Ward and Merrigan 1992). The device utilizes an acoustic resonator in which a standing wave is established. A stack of short plates are positioned at one end of the resonator, with heat added at one end of the length of the plates, and heat removed at the other end, the ends being held at the cycle hot and cold temperatures, respectively. The position and length of the plates is designed to place the hot end of the plates at a pressure maximum and the cold end at a pressure minimum in the standing acoustic wave. The effect is to add energy to the gas between hot and cold end, resulting in a traveling acoustic wave which transfers energy to the transducer.

The plate stack is the most important component in the thermoacoustic converter as its design has the greatest affect on converter performance. The spacing between plates is determined by the thermal penetration depth of the fluid, which in turn is dependent on operating temperature. Actual devices have utilized spiraled sheet material, honeycomb and blocks with parallel square channels. The power output required from the converter determines the diameter of the resonator at the plate stack end.

Working fluids for the thermoacoustic converter may be either gas or liquid metal with engines having been built with air, helium, argon, helium/argon, or helium/xenon mixtures, and liquid sodium. For space power systems the high heat rejection temperatures required to minimize radiator area would likely dictate the use of liquid metals. Piezoelectric transducers used for gas systems would depolarize at high temperature, whereas a liquid metal system could utilize an MHD transducer.

Performance characteristics for 1kW engine designs using helium and liquid sodium as working fluids were given by Ward and Merrigan (1992). They project overall thermal-to-electric conversion efficiencies in the 15%-21% range for these engines at T_{hot}=1100K and T_{cold}=330K. No studies have been reported that integrate thermoacoustic engines with a radioisotope or reactor-based heat source. Thus, this technology is at a very early state of development with little data being available to fully ascertain the technical issues involved in reducing thermoacoustic engines to practice in space systems. For example, the optimum design for integration with a heat source and lifetime limiting processes in a system must be determined. Also, vibration may be an issue for some applications, and thus, its effects and possible means to minimize vibration require study. Component and converter experimental data must be combined with a system design to begin to answer these questions and permit evaluation of thermoacoustic engines as an option for space nuclear power systems.

LIQUID METAL MAGNETOHYDRODYNAMICS

Blumeneau et al. (1988), and Fabris (1992) reviewed the status of liquid metal magnetohydrodynamics at the 1987 and 1989 Symposia, respectively. Work on this technology was carried out from the 1960's into the 1980's, but little experimental work has been carried out in recent years. However, the cycle does offer the benefits of a static device and has the potential for operating efficiencies of 10-15% over a range of power levels. The simplest form of an LMMHD cycle is shown in Figure 5a. Here, a single component liquid metal is heated via reactor (or possibly radioisotope) heat source to a partial boiling state, whereupon it enters the two-phase MHD generator (Figure 5b).

Work is extracted as the two-phase mixture expands isentropically through the divergent duct of the MHD generator. In the expansion, the pressure drops, additional liquid vaporizes, and the temperature falls. The two-phase mixture is subsequently cooled in the rejection heat exchanger and pumped, via electromagnetic pump, back to the heat source. This cycle is called by Blumeneau et al. (1988) a "wet-vapor" cycle and could incorporate multiple MHD stages for higher efficiencies.

There are different variations on the LMMHD cycle, including some that add a second liquid metal fluid, of high vapor pressure, upstream of the MHD generator that vaporizes to aid in accelerating the liquid flow. Variations in cycle concepts involve whether or not to place a liquid/vapor separator before the MHD generator. The separator is a source for losses, if used; while the MHD generator may not operate efficiently if operated in a two phase flow regime. Most recent concepts have focused on operating the MHD generator in the two-phase mode. However, the losses encountered remain so substantial that experimental efficiencies reported to date are usually substantially less than 10%. These losses usually involve inefficient energy tranfer between vapor and liquid phases in the two phase flow or drag losses at various points in the cycle.

System concepts for LMMHD have typically addressed reactor-based systems from tens of kilowatts to hundreds of megawatts, with single MHD-stage system efficiencies possibly reaching 10%. Efficiencies above 10% would probably require two- or three- stages of MHD generators. For example, a 100-MW_e, three-stage, cesium wet-vapor cycle system was projected to have a system efficiency of 11.6%. On the other hand, the radiator area required for such a system was competitive with most other concepts at the time since the heat rejection temperature was 1123K (T_h=1673K).

The highest projected efficiencies are predicated on achieving high (approx 90%) vapor volume fraction in the MHD generator. Research work has recently been directed toward this issue, focused on the possibility of adding surfactants to the liquid metal to promote foaming (Fabris et al. 1990). Projections show that a high efficiency (70+%), high void fraction (92%) MHD generator should be feasible (Fabris et al. 1992). However, until these calculations are verified by basic experiments, the relatively small increases in efficiency now offered by LMMHD do not justify a development program for space power applications. Also, further concept work is needed at lower temperatures and in small size ranges to evaluate systems that might be applicable to radioisotope heat sources.

SUMMARY

The combination of efficiency (13%) and lifetime demonstrations (several thousand hours) with AMTEC cells establishes it as the most advanced of the technologies reviewed here. AMTEC technology work is continuing to demonstrate key system lifetime and performance goals, to be followed by a space experiment. Thermophotovoltaic conversion is based on a well developed solar cell technology and needed cavity tests are presently being planned to answer key performance issues before further development would be initiated. HYTEC is in the same family of conversion technologies as AMTEC, but is based on a different working fluid and is still in its early stages of basic development work. Thermoacoustic generators have not been studied extensively for space applications and an experimental plan based upon space requirements is needed before a development program is warranted. Finally, liquid metal MHD requires a basic advance in two phase flow technology to warrant significant development attention. Thus, AMTEC is a definite candidate for space power applications; thermophotovoltaics could become viable if upcoming experiments are successful; HYTEC experiments must provide a complete understanding of that cycle to establish its viability; and thermoacoustics and liquid metal MHD are still far from establishing feasibility for space applications.

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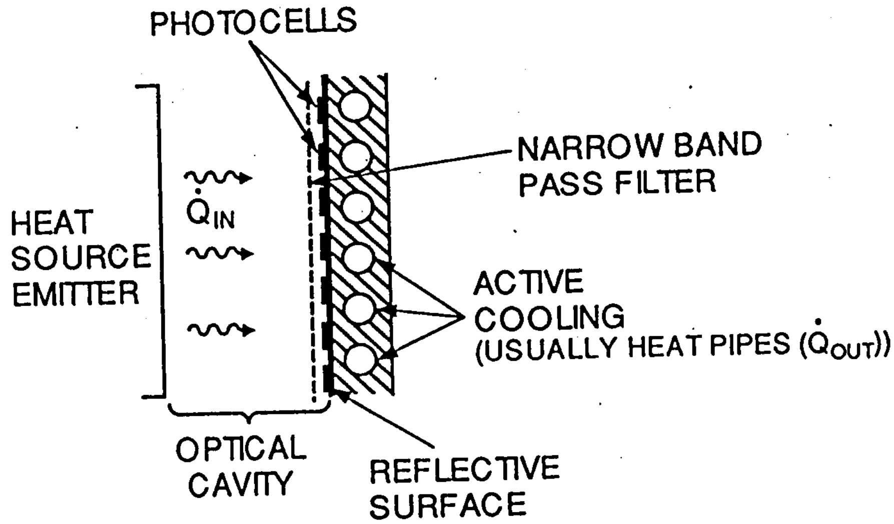

FIGURE 1. Thermophotovoltaic Schematic.

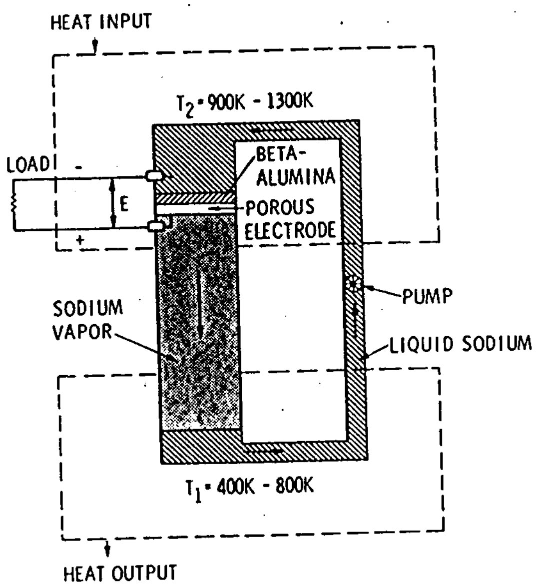

FIGURE 2a. AMTEC Schematic.

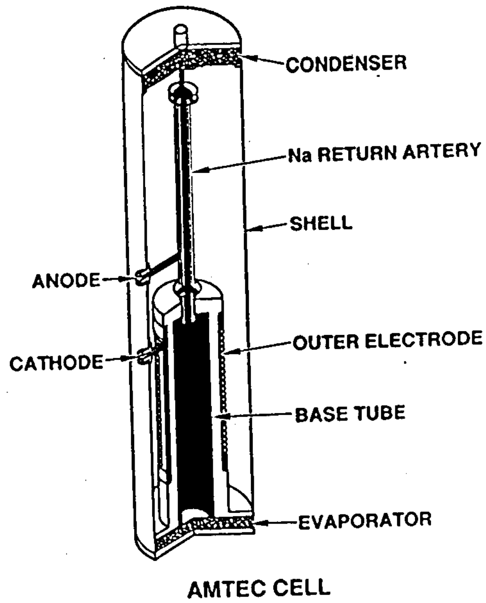

FIGURE 2b. AMTEC Space Cell Concept Design.

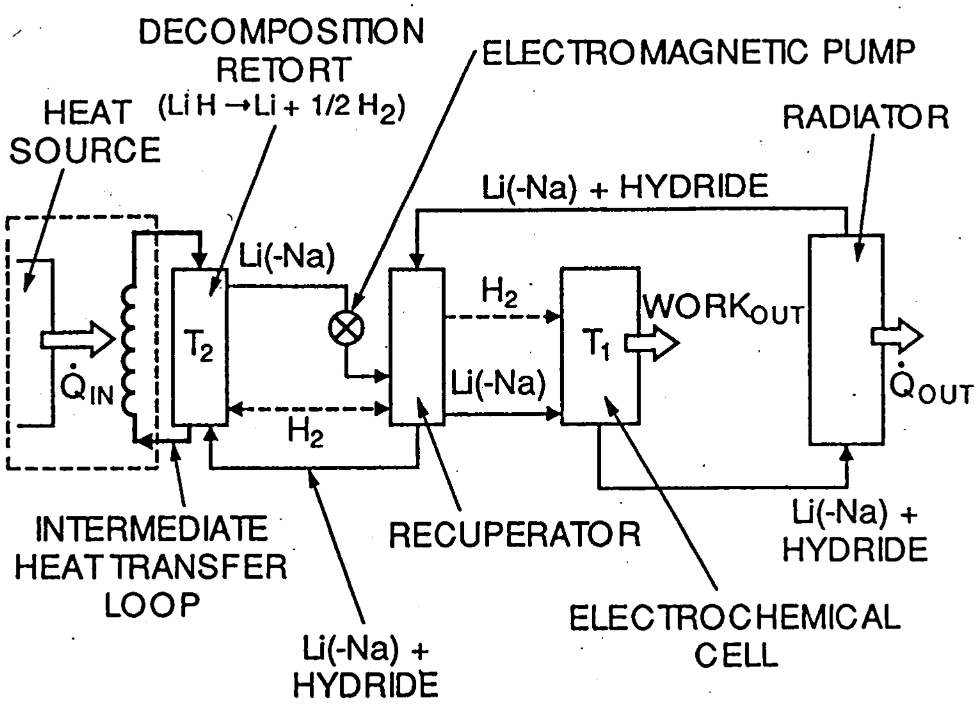

FIGURE 3a. HYTEC Cycle.

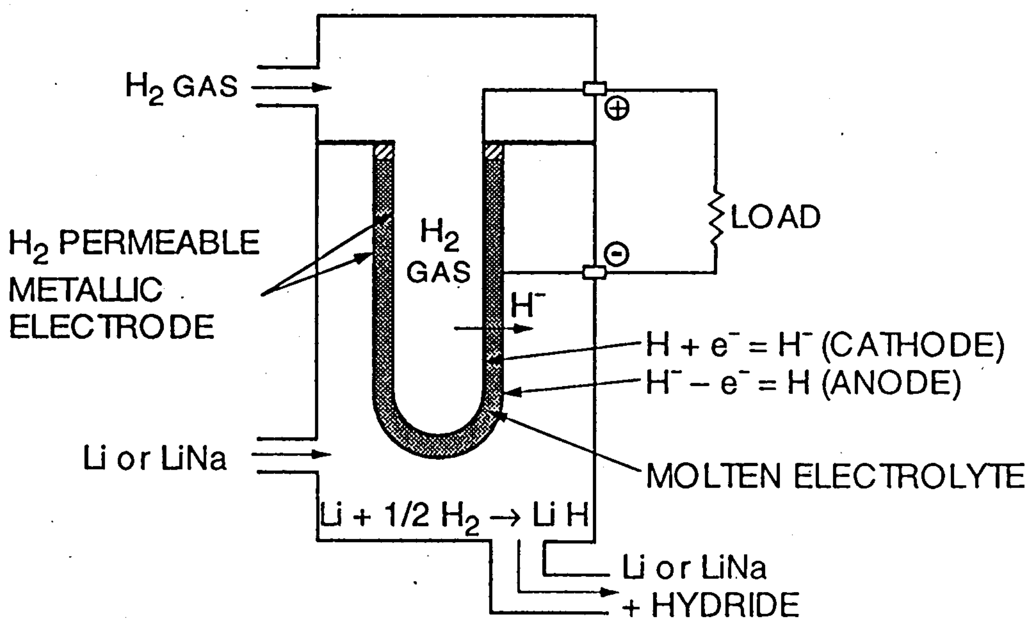

FIGURE 3b. HYTEC Electrochemical Cell.

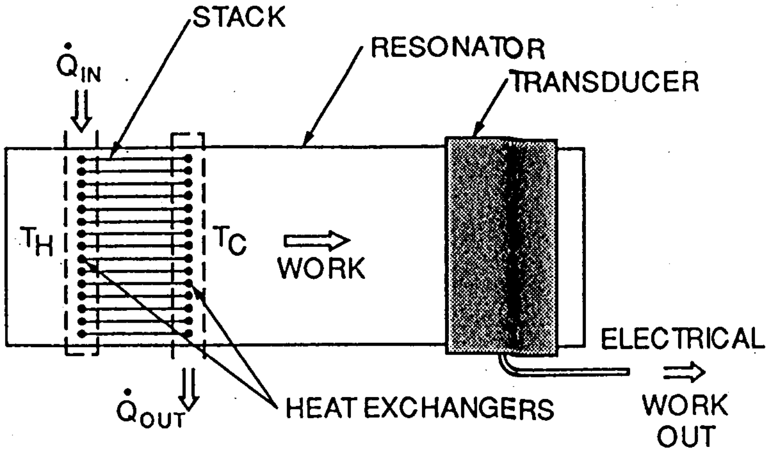

FIGURE 4. Thermoacoustic Converter Schematic.

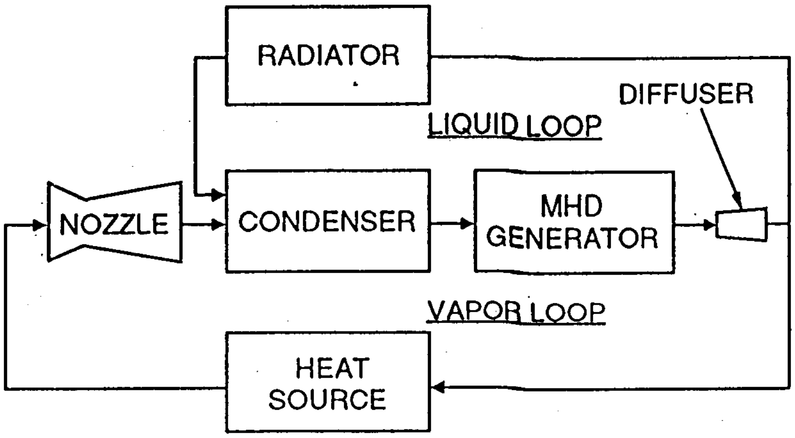

FIGURE 5a. LMMHD Condensing Cycle.

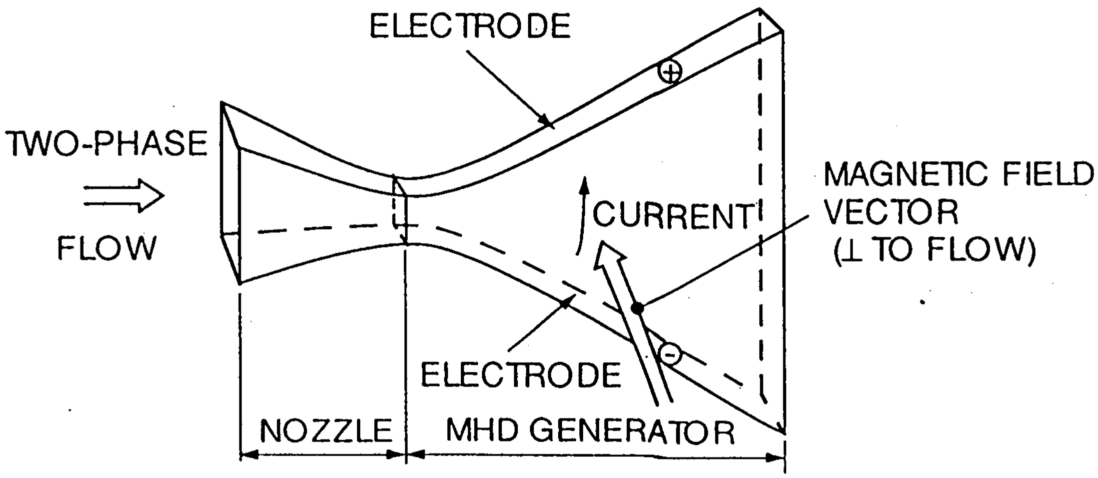

FIGURE 5b. MHD Generator.